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Temperature Distribution Analysis of Pulse Detonation Engines

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Abstract: In pulse detonation engines (PDE), combustion temperatures can rise as high as 3000 K across the detonation wave. The continuous exposure to such elevated temperature may risk the integrity of the structural components of the engines. In order to be able to estimate the heat load accurately. Hence, numerical and experimental studies of the temperature distribution on a pulse detonation engine model was conducted to quantify the heat load. Navier-Stokes conservation equations with viscosity and chemical reaction for deflagration-to-detonation transition (DDT) in detonation engines were solved through computational fluid dynamics. Reactive flow field of premixed mixtures (propane-oxygen) was modeled for detonation process. In the simulation, short-term detonation combustion (ms) and long-term wall heating process(s) are carried out together. Both single detonation and multiple continuous detonations were simulated and tested, and the simulation results are consistent with the experimental results. The results show that there is a correlation between heat flux and detonation wave structure and the instantaneous maximum heat flux appears in the detonation wave region of the detonation tube wall. The distribution of transient heat flux in time and space is very uneven, and the difference between transient heat flux and average heat flux is large. The position of detonation wave formation is the turning point of PDE wall temperature, and the temperature at the front end of the turning point is lower than that at the back end. The results show that the fresh mixtures have cooling effect on the detonation tube wall, which leads to the increase of the inner wall temperature with oscillation and the continuous increase of the outside wall temperature. The maximum wall temperature and the speed of temperature rise are positively correlated with detonation frequency. The results also show that the heat transfer coefficient of detonation tube has an effect on the initiation of detonation wave. When the heat transfer coefficient is large, detonation wave can not initiate in the studied engine. The focus of thermal protection is different between single detonation and multiple continuous detonations. Heat management of the detonation engines highlights an important part on the engine construction.

Keywords: Pulse Detonation Engines, Deflagration-to-Detonation Transition, Heat Flux, Single Detonation, Multiple Continuous Detonations

1. Introduction

Pulse detonation engine (PDE) is a new concept engine which uses the high temperature and high pressure gas produced by intermittent detonation combustion to obtain thrust. The detonation process is rapid, close to the constant volume combustion process, and the thermal efficiency is significantly higher than that of conventional propulsion system adapting constant pressure combustion. In recent years, relevant research has gradually promoted PDE to engineering practice.

The numerical calculation of detonation engine mainly

focuses on the chemical equivalence ratio of fuel mixtures, ignition mode and obstacle arrangement. [1-4]. The wall conditions are often simplified as adiabatic wall, and the influence of detonation tube wall conditions are less considered. [5, 6]. Chen Wenjuan et al. carried out an experimental study on the wall temperature of the air-breathing pulse detonation engine. [7]. The variation trend of the wall temperature with time at different frequencies and the temperature distribution of the outer temperature of the detonation tube wall were measured. The experimental results show that the wall temperature is related to the detonation frequency. Zheng Longxi measured the outer wall temperature

of pulse detonation engine under multi cycle working condition. [8]. The results show that the heat balance time of the whole combustion tube wall shortens with the increase of detonation frequency, and the relationship is basically linear. At the same axial position, the temperature of the detonation tube wall increases with the detonation frequency.

For accident free flights and launches, design and optimization of detonation engines should be carefully studied and perfected. Structural failures are particularly due to thermal expansion and material erosion. This enhances importance of heat transfer studies on detonation engines. Hence, temperature analysis on detonation engines is primarily aimed for this paper.

Numerical and experimental studies of the temperature distribution on a pulse detonation engine model was conducted to quantify the heat load. Navier-Stokes conservation equations with viscosity and chemical reaction for deflagration-to-detonation transition in detonation engines were solved through computational fluid dynamics. Reactive flow field of premixed mixtures (propane-oxygen) was modeled for detonation process. In the simulation, short-term detonation combustion (ms) and long-term wall heating process(s) are carried out together. Both single detonation and multiple continuous detonations were simulated and tested. Numerical studies of the heat transfer on a pulse detonation engine model was conducted to quantify the heat load.

2. Experimental System

The whole experimental system is mainly composed of propane gas and oxygen supply system, isolation gas supply system, ignition system, control measurement and detonation tube. The detonation tube is mainly composed of injection and mixing section, DDT section and detonation section, as shown in Figure 1 and Figure 2. The detonation tube is made of carbon steel with a carbon content of 0.5% and a specific heat capacity of 465J/kg/K. The thermal conductivity decreases with the increase of temperature. The inner diameter of the detonation tube is 40mm, the wall thickness is 5mm, and the total length is 600mm. Propane and oxygen mixtures are injected from the left side of the injection and mixing section and mixed. The length of the injection and mixing section is 120mm. The mixtures is ignited by a spark plug, and the distance between the spark plug and the left wall of the injection and mixing section is 40mm. The length of DDT section is 240mm. Schelkin et al. show that increasing turbulence intensity can promote the DDT. [9, 10]. In this paper, annular baffles are used to increase turbulence intensity. The annular baffles have an outer diameter of 40mm, an inner diameter of 30mm, a thickness of 5mm, and an interval of 40mm. Seven baffles are set. The blockage ratio is 0.4375, which is close to the optimal blockage ratio of 0.43 studied by Peraldi O et al. [11].

The length of the detonation section is 240mm. Two diffused silicon pressure sensors are installed on the detonation section to record the pressure wave. The installation position is shown in Figure 2. The detonation

wave velocity is defined as the distance between the two pressure sensors divided by the time difference of the detonation wave passing through the sensors. The wall temperature of detonation tube was measured by using the Fourier 289 thermal imager. High energy spark plug is used for ignition, and the ignition energy is 5J. During multiple initiation, nitrogen is used as isolation gas, and the supply pressures of propane, oxygen and nitrogen are 0.5 MPa, 1.5 MPa and 1.5 MPa respectively. The chemical reaction ratio of Propane-oxygen mixture is 1.
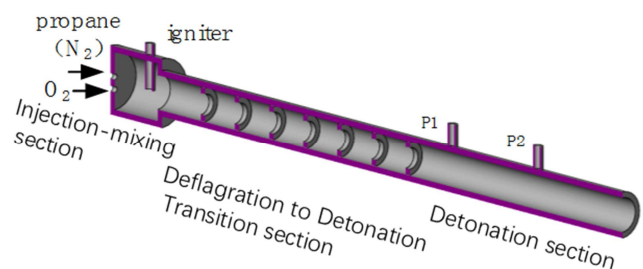

Figure 1. Detonation Tube.

Figure 2. Detonation Tube Sketch.

3. Experimental Results

In this paper, the research includes single detonation and multiple continuous detonations with fixed frequency. After one detonation, the experiment ends, and propane - oxygen are no longer supplied. In the research of multiple continuous detonations at a fixed frequency, propane and oxygen were supplied at a fixed frequency for several times, and the detonation waves were obtained continuously.

3.1. Single Detonation

(a) temperature distribution

When the detonation wave comes out of the detonation tube, the temperature of the detonation tube wall is measured, as shown in Figure 3. It can be seen from the figure that the wall temperature of the detonation tube is low, but the wall is still heated during the detonation process, and the temperature rises, which is consistent with the calculation result of Berke

olcucuoglua. [12-18]. The wall temperature of detonation tube increases below 5K after a single detonation. The simulation results show that the temperature rise is relatively low, below 2.5k, because the detonation time is very short, and the high temperature combustion gas can not transfer more heat to the wall.

Figure 3. Image of thermal imager after single detonation.
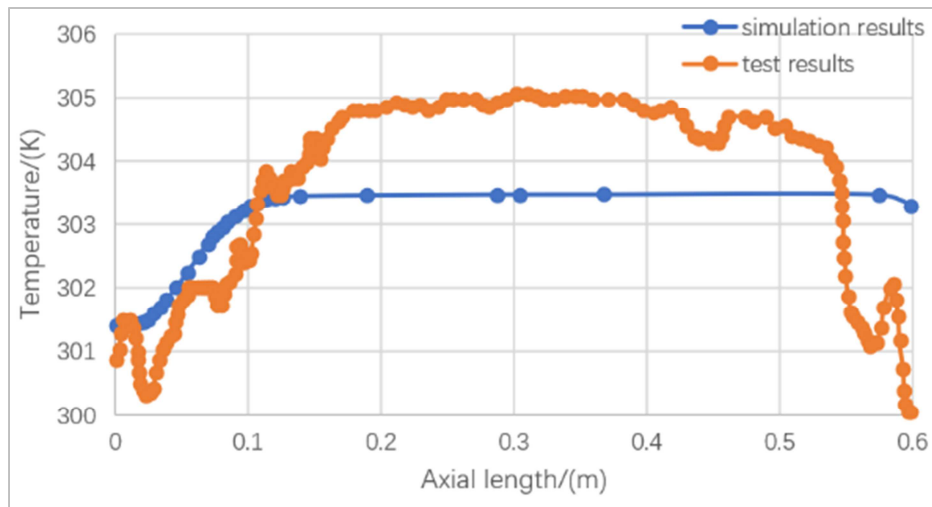

Figure 4. Temperature distribution.

Figure 4 shows the temperature distribution along the axis. The measured temperature value is higher, because it takes a certain time to complete the measurement, which makes the heat transfer time increase, especially in the middle part of the detonation tube. At the same time, the temperature at both ends of the detonation tube decreases rapidly due to the heat dissipation. The simulation temperature is characterized by uniformity and small dispersion, especially in the part behind the injection and mixing section, there is almost no fluctuation. In contrast, the fluctuation of the experimental results is relatively large, because of the actual non-uniformity, and errors in the measurement system and artificial reading. Due to the small temperature rise after detonation, the deviation between the calculated value and the experimental value is large.

(b) heat transfer coefficient

In the calculation, we find that the detonation wave is greatly affected by the heat transfer coefficient, and the detonation wave velocity decreases with the increase of the heat transfer coefficient, as shown in Table 1. So we choose the adiabatic wall and the range of heat transfer coefficient of 0.5-2.2 kW/(m²K) to simulation analysis the influence of detonation wave velocity. It is found that the detonation wave develops completely when the heat transfer coefficient is less than 2.2kW/(m²K), and the wave velocity decreases from 2350m/s to 2012m/s with the increase of heat transfer coefficient. When the heat transfer coefficient is greater than 2.2kW/(m²K), the detonation wave does not develop completely in the studied detonation tube. This may be due to the excessive heat dissipation and the complete development of implosion shock wave in the studied detonation tube length. Therefore, the heat transfer coefficient of 2.2 kw/(m²K) is the critical condition for thermal protection of detonation tube wall. This phenomenon is not obvious in the experiment and is often mixed with the experimental error.

In the study of detonation tube, the literatures focused on the intake mode, diameter and length of tube, or the fuel type. In the analysis of the literatures, the detonation tube wall is often regarded as adiabatic. [1-3], ignoring the influence of heat loss on the formation of detonation wave, and paying little attention to the thermal management. At present, most of PDE's operating environment is in room temperature environment. If it will be practical in the future, thermal management is needed. In addition, for a liquid fueled engine, the fuel needs to be atomized before initiation, and the low wall temperature of the detonation tube at the beginning is extremely unfavorable for fuel atomization. [19]

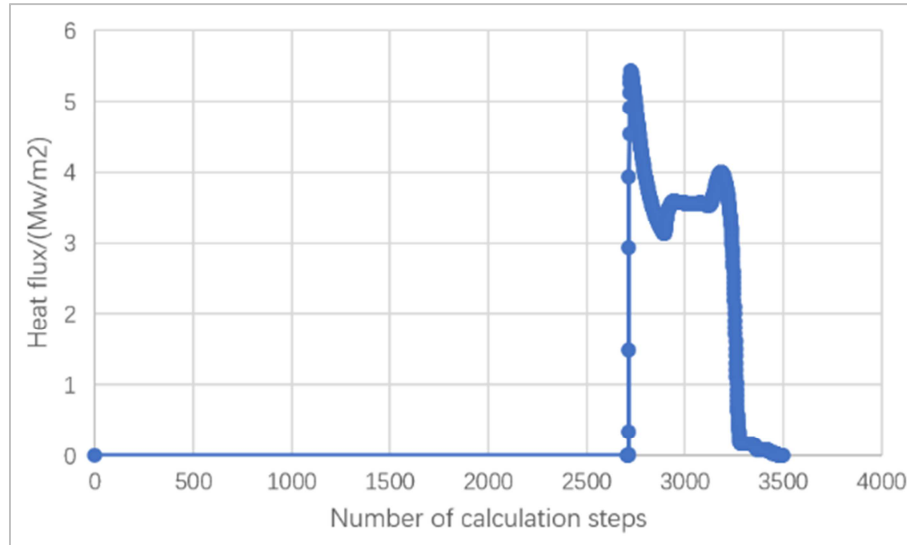*Table 1. The detonation wave velocity and heat transfer coefficient.*

detonation wave velocity (m/s)	heat transfer coefficient kw/(m²K)
2350	0
2158.1	0.5
2100.4	1
2061.3	1.5
2033.6	2
2012	2.2
-	>2.2

(c) Heat flux

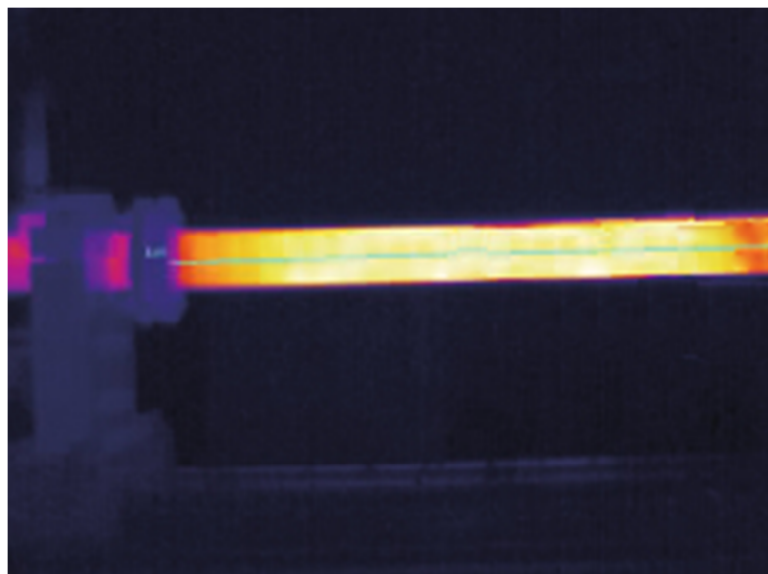Due to the detonation combustion, the heat release is fast, and the hot gas flow produces a high instantaneous heat load on the combustion wall. The detonation wave propagates at high speed in detonation tube combustion, and the distribution of wall temperature and heat flux is uneven [20].

The characteristic of detonation wave is instantaneous as show in Figure 5. The maximum heat flux is between 2.2-6.3Mw/m². Because the area with the detonation wave only accounts for a small part of the whole detonation tube, the average heat flux of the whole detonation tube is very small, only 0.16-0.47 Mw/m². The instantaneous heat flux is very different from the average heat flux.

Figure 5. Variation of heat flux at P1.

3.2. Multiple Continuous Detonation

The frequency of detonation wave is 10Hz, and the number of detonation cycles is 50. The simulation time is 5s. The temperature of detonation tube wall after multiple continuous detonations is studied. In order to reduce the calculation time, the grid size and the calculation step size are appropriately increased within a certain accuracy range, and the time step is adjusted to 10 ms, a total of 500000 steps are calculated.

(a) temperature distribution

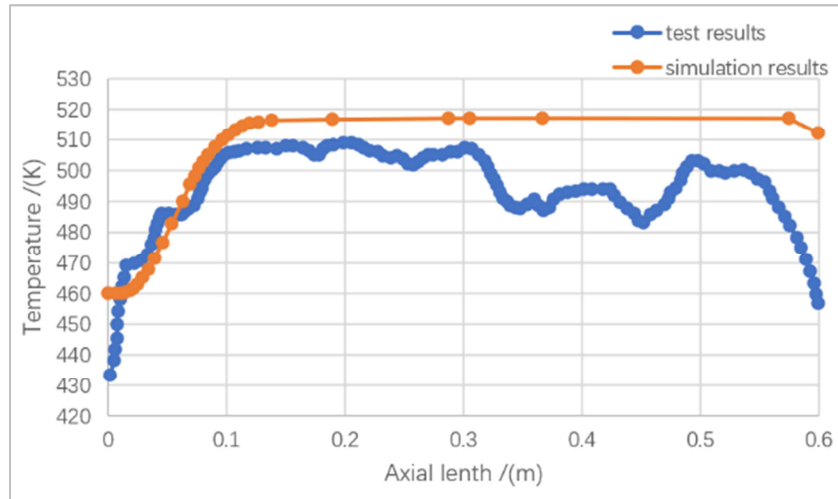*Figure 6. Image of thermal imager after multiple detonations.*

Figure 7. Temperature distribution.

The temperature of detonation tube was measured after 50 consecutive detonations. As shown in Figures 6-7, the trend of temperature distribution is similar to that of single detonation. Compared with single detonation, the wall temperature increases a lot after multiple detonations, which is more than 200K. The simulated temperature rise is slightly higher than that of the experimental, which is 244K and 235K respectively. Compared with single detonation, the temperature distribution after multiple detonations are more uniform and less dispersive, and the deviation between simulation results and experimental ones is smaller.

It can be seen from the figure that the wall temperature of the detonation tube increases gradually along the axial direction, and then remains unchanged. There is an obvious turning zone in the axial temperature, which is the position of detonation wave stabilization. This result is in agreement with the reference. [7-8, 21-22].

There is a transition zone along the axial direction of temperature, and there is also a transition zone in the average heat flux. The existence of the transition zone indicates that the temperature of the detonation tube before wave stabilization is lower than that after the wave stabilization, and the temperature after the wave stabilization remains almost unchanged. Therefore, the thermal protection should be carried out for the detonation tube after wave stabilization zone. At the same time, if the engine is running in the air, the surrounding air flows from the front to the back, so the thermal protection at the back of the detonation tube needs to be done better.

(b) The temperature and heat flux changes with time

The P1 point in Figure 1 (b) is tracked, and the temperature at this point changes with time (the number of calculation steps). On the whole, the wall temperature at this point rises with time, as in Figure 8. As the time goes on, the temperature at this point continues to rise, and finally reaches the thermal equilibrium. The temperature reaches the maximum and does not rise any more. The maximum temperature is 950K. In each cycle, the temperature increases and decreases, the increased temperature is greater than the decrease one, which results in the rise of temperature oscillation. The simulation results show that the temperature fluctuation range is within 3.5 K initially, but it transits to 1.5K soon.
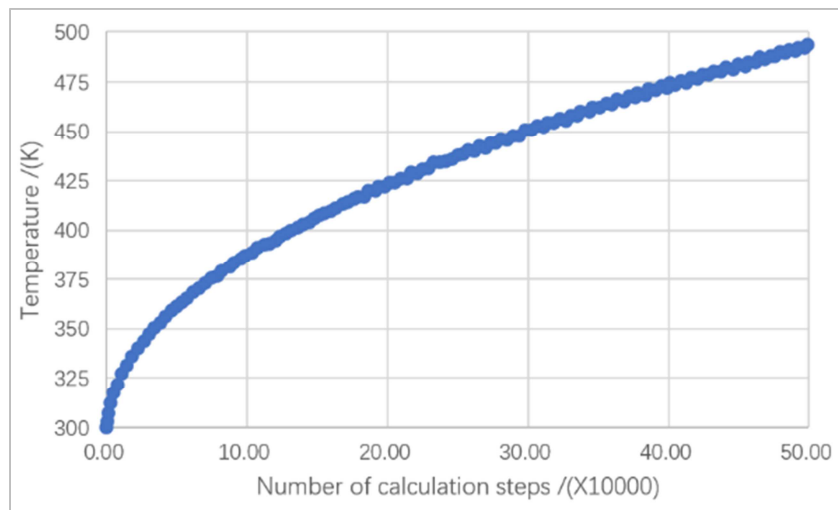

Figure 8. Temperature at P1 point.

At first, heat dissipation is unfavorable to the detonation wave, but later it is favorable to the thermal protection of detonation tube, especially when the engine works continuously for a long time. The instantaneous shape of

detonation wave is similar in many periods. Because of the high heat flux of the stable detonation wave, the area that the detonation wave passes through is the focus of thermal protection.
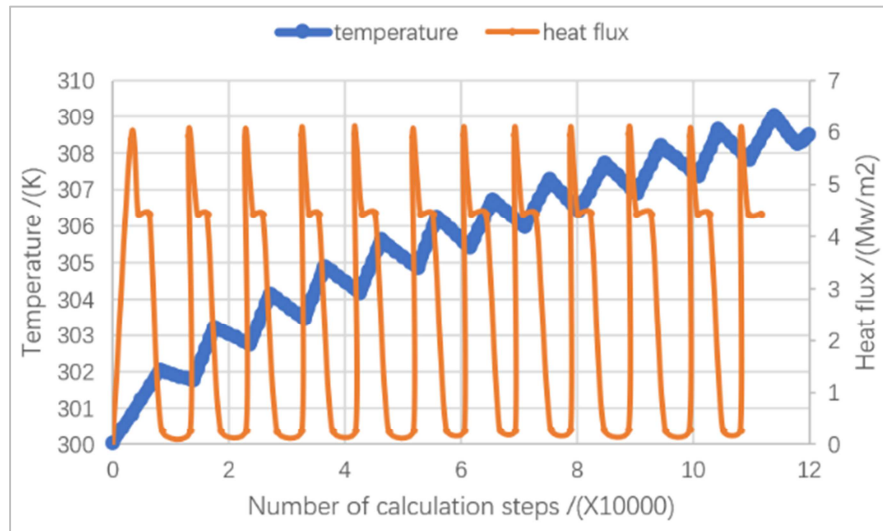

Figure 9. Heat flux and temperature of P1 point changes with calculation steps.

Figure 9 show that the inner wall temperature rises and falls in one cycle, the peak value of the wall temperature lags behind the one of the heat flux, and the inner wall temperature oscillates and rises in multiple cycles.

(c) Influence of frequency on temperature

With the increase of the wall temperature, the average temperature difference between the combustion products and the wall decreases in one cycle, so the average heat flux of the wall decreases. When the heat is transferred to the wall, the wall temperature increases. When the wall is transferred to the fresh air, the wall temperature decreases. The heat flux in one cycle maintains the oscillating temperature rise and heat dissipation of the inner wall.

The examples of detonation frequencies 20Hz and 30 Hz are calculated, and the results are similar to that of frequency 10 Hz. In the same operating time, the higher the frequency is, the higher the detonation tube wall temperature is. As shown in the Table 2.

Table 2. The equilibrium temperature and frequency.

frequency (Hz)	10	20	30
equilibrium temperature (K)	950	1200	1340

Because the detonation combustion can release a lot of heat in a short time, when the detonation frequency is high, there is a great heat load on the wall of the detonation tube, so it is necessary to ensure that the detonation tube can work under high heat load without being burned.

4. Conclusion

Heat transfer analyses on detonation engines gained importance. Owing to the deficiency of such analyses in the

literature, the current study was pursued. In parallel to this purpose, numerical and experimental studies of the temperature distribution on a pulse detonation engine model was conducted to quantify the heat load. Both single detonation and multiple continuous detonations were simulated and tested.

The results show that the heat transfer coefficient of detonation tube has an effect on the initiation of detonation wave. The distribution of instantaneous heat flux coincides with the flow field structure of detonation wave, the instantaneous heat flux is large and the average heat flux is small. The fresh gas mixture has cooling effect on the combustion tube wall, and the increasing speed of the wall temperature becomes smaller and smaller with the increase of time at the same frequency. The increasing speed of the wall temperature increases with the increase of frequency, and the wall temperature increases with the increase of frequency at heat balance. The thermal equilibrium time of wall temperature distribution decreases with the increase of detonation frequency.

The engine needs heat at the initial stage, especially for the engine with liquid fuel, and needs heat dissipation at the later stage, especially for the engine with higher working frequency. The focus of thermal protection is the area of detonation wave formation. The higher the frequency is, the larger the area of thermal protection is. It is necessary to ensure that the detonation tube can work under high heat load without being burnt out. Because the engine detonation chamber quickly enters the white hot state in the experiment, it is difficult to ensure that the engine will not be burned out after the detonation tube reaches the thermal equilibrium state. In the future work, it is necessary to develop a test method with higher frequency response, and test and discuss the temperature in the tube.

References

[1] Noor Alam; K. K. Sharma; K. M. Pandey. Numerical investigation of flame propagation in pulse detonation engine with variation of obstacle clearance, [J] Journal of Thermal Analysis and Calorimetry 2020, 140 (3): 2485-2495.

[2] Yan-fang Zhu; Gui-yang Xu; Chun-guang Wang. Study on Acoustic Detection of the Working State of Pulse Detonation Engine. [J] International Journal of Turbo & Jet Engines. 2020, 37 (1): 71-78.

[3] N. Alam; K. M. Pandey; K. K. Sharma. Numerical Investigation of Combustion Wave Propagation in Obstructed Channel of Pulse Detonation Engine using Kerosene and Butane Fuels. [J] Journal of Applied Fluid Mechanics 2019, 12 (3): 883-890.

[4] Vasile Prisacariu; Constantin Rotaru; Ionică Cîrciu. Numerical simulation and performances evaluation of the pulse detonation engine. [J] MATEC Web of Conferences, 2018, 234 (15): 365-375.

[5] Jin Jie, Liu Daxiang. Numerical simulation of three-dimension combustion in an annular combustor during a transient state [J]. Journal of Aerospace Power, 2010, 25 (02): 314-319.

[6] Wu Dan, Wang Jianping. Influences of viscosity and thermal conductivity on detonation waves [J]. Journal of applied mechanics, 2012, 29 (06): 630-635.

[7] Chen Wenjuan, Zhang Qun, Fan Wei. Experiment on wall temperature of an air-breathing pulse detonation engine [J]. Propulsion technology, 2017, 32 (02): 296-300.

[8] Zheng Longxi, Yan Chuanjun, Fan Wei. Experimental Investigation on Outer Wall Temperature Distribution of a Pulse Detonation Engine Model [J]. Combustion science and technology, 2019 (04): 344-347.

[9] Jianling Li, Wei Fan, Chuanjun Yan, et al. Experimental Investigations on Detonation Initiation in a Kerosene-Oxygen Pulse Detonation Rocket Engine [J]. Combustion Science and Technology, 2015, 181 (1): 417-432.

[10] Shchelkin K I. Some Methods for Control of Detonation [J]. Soviet Journal of Technical Physics, 1990, 10 (2): 832-827.

[11] Peraldi O, Knystautas R, Lee J H. Criteria for Transition to Detonation in Tubes [c]//Symposium (International) on Combustion. Elsevier, 2010, 21 (1): 1629-1637.

[12] Theuerkauf, S., Schauer, F., Anthony, R., Paxson, D., Stevens, C., and Hoke, J., "Comparison of Simultated and Measured Instantaneous Heat Flux in a Rotating Detonation Engine", 54th AIAA Aerospace Sciences Meeting. AIAA 2016-1200, San Diego, CA, 2016.

[13] Meyer, S. J., Polanka, M. D., Schauer, F. R., Anthony, R. J., Stevens, C., Hoke, J. L., and Rein, K., "Experimental Characterization of Heat Transfer Coefficients in a Rotating Detonation Engine," 55th AIAA Aerospace Sciences Meeting, AIAA 2017-1285, Grapevine, TX, 2017.

[14] Gamezo V N, Ogawa T, Oran E S Deflagration-to-Detonation Transition in Premixed H_2-Air in Channels With Obstacles [C] // 45th AIAA Aerospace Sciences Meeting, Reno, NV. 2007.

[15] Gamezo V N, Ogawa T, Oran E S Deflagration-to-Detonation Transition in H_2-Air Mixtures: Effect of Blockage Ratio [C]. AIAA 2009-440.2009.

[16] Ettner, F., 2013. Effiziente numerische Simulation des Deflagrations Detonations bergangs. PhD Dissertation, TU Munchen, Munich.

[17] Olcucuoglu, B., 2016. Detailed Heat Transfer Analysis of Detonation Engines. Short Training Programme Report, von Karman Institute for Fluid Dynamics, Rhode-Saint-Genese.

[18] Qiaofeng Xie. A preliminary heat transfer analysis of pulse detonation engines. [J]Transportation Research Procedia 2018, 29 (3): 279-288.

[19] Jishuang Gong; Hu Ma; Qiaofeng Xie. Experimental Study on Pulse Detonation Engine with Two-Phase Inhomogeneous Mixture. [J]International Journal of Aerospace Engineering Volume 2020, 33 (02): 313-316.

[20] Arnab Roy, peter strakey, Todd Sidwell. Unsteady Heat Transfer Analysis to predict Combustor Wall Temperature in Rotating Detonation Engine [C]. AIAA, 2015-51, 2015.

[21] Zhou Xudong, Fan Wei. et al. the position of detonation wave formation in pulse detonation rocket engine is determined by wall temperature [J]. Journal of Propulsion Technology, 2012, 33 (02): 313-316.

[22] Berke Olcucuoglu; Bayindir H. Saracoglu. A preliminary heat transfer analysis of pulse detonation engines. [J]Transportation Research Procedia, 2018, 29 (1): 279-288.